

# 95 MILLION PIXEL FOCAL PLANE FOR USE ON THE KEPLER DISCOVERY MISSION

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**Abstract:** The primary goal of the upcoming *Kepler* Discovery mission is to search for terrestrial size planets around neighboring stars. To accomplish this mission, a space-based photometer is being developed that employs a 0.95m aperture Schmidt telescope coupled to a very large focal plane array (FPA) measuring 14" (L) x 14" (W) x 10" (D). The FPA is populated with 42 large format custom CCD-based detectors to yield approximately 95 million pixels in the 100 square degrees field of view of the instrument. Over the 4 year mission the FPA will continuously measure the relative intensity of approximately 100 thousands main sequence stars ( $14 = m_v = 9$ ) and will be capable of detecting relative changes in stellar flux on the order of 10-40 ppm (one-sigma) over transit periods ranging between 2 to 16 hours. All critical electronics are housed immediately behind the FPA, which yields a low noise, compact design that is both robust and fault tolerant. The design and development of the FPA and custom CCD-based detectors is discussed along with the results from detailed performance models.

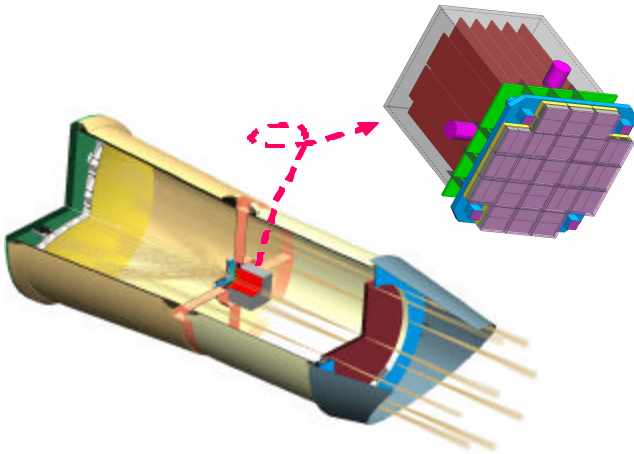
**Key words:** *Kepler*, CCD, FPA, Photometry

## 1. INTRODUCTION

The primary goal of the *Kepler* Discovery Mission [1] is to survey at least 100 square degrees of the sky for at least 4 years while gathering relative intensity data on approximately 100 thousand main sequence stars, ranging in brightness from  $14 = m_v = 9$ . To accomplish this task a 0.95 meter aperture space-based photometer is being developed by Ball

Aerospace & Technologies Corporation for the *Kepler* science team headed by NASA Ames. The stream of stellar intensity data will be analyzed on the ground to identify planetary transient events ranging in duration from 2-16 hours. Of particular interest to the science team will be the identification of transit events corresponding to planets lying in the habitable zone [2]. The *Kepler* spacecraft will reside in a heliocentric orbit to take advantage of the benign observing environment, with the launch currently scheduled to occur in 2007.

At the heart of the *Kepler* photometer, as depicted in Figure 1, is the Focal Plane Array Assembly (FPAA), which consists of the integrated Focal Plane Array (FPA) and Focal Plane Interface Electronics (FPI). The FPA is populated with a total of 46 CCD-based detectors and is tasked with monitoring the star ensemble. Of the 46 CCDs, 42 are dedicated to the acquisition of science data and remaining 4 CCDs are used for fine guidance control. The 42 science CCDs are arranged onto 21 CCD modules, with each module housing 2 CCDs. The FPI lies immediately behind the FPA and supplies all critical bias and clock inputs and pre-amplification of the CCD output signals. All electrical signals are routed to/from the FPAA through cables along the spider support legs.

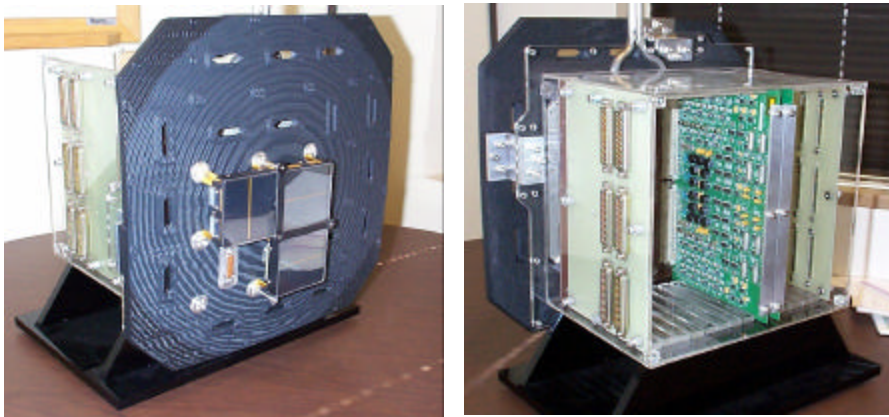


*Figure 1 Transparent view of preliminary Kepler photometer design*

Every 90 days the *Kepler* spacecraft will undergo a 90° rotation about the optical axis to keep the solar panels optimally aligned to the sun and the passive radiator pointed to deep space. During this period a number of system level checks will be performed and an entire field of view image (i.e. a 95 million pixel image) will be downloaded, along with other telemetry data. After thermal stability is reestablished (<24 hours), the instrument re-

starts the continuous monitoring functions. During the monitoring periods, only select regions around each star of interest, referred to as photometric apertures, will be downloaded to the ground. The particular photometric aperture selected for a given star will be determined through statistical analysis, as discussed by Jenkins [3].

Figure 2 shows two views of the mechanical FPAA model populated with only three CCD modules and two FPI electronics boards. The FPA is cooled using dual constant conductance heat pipes and a dedicated passive radiator. Additional details on the FPA, FPI, CCD module, and science CCD are discussed in the following sections.



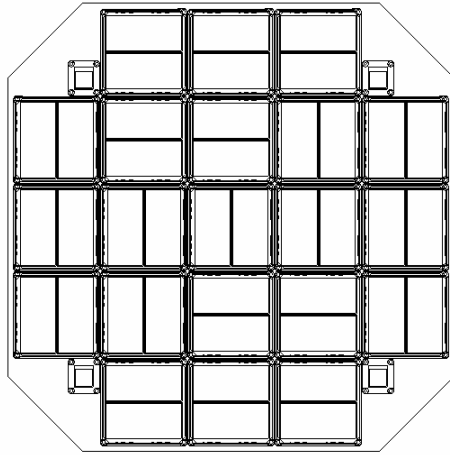
*Figure 2 Front and rear views of the mechanical FPAA model  
(black base is not part of the FPAA)*

## 2. FOCAL PLANE ARRAY

The Focal Plane Array (FPA) consists of a 14" x 14" substrate made from graphite cyanate ester onto which 25 CCD modules (21 science and 4 fine guidance) are mounted. The curvature of the substrate is designed to match the optimal focal surface of the Schmidt telescope, which is closely described by a 1.4 meter spherical surface. Molybdenum inserts are spaced across the curved FPA surface to provide a mechanically stable platform and a high conductivity thermal path to the 'thermal spreader' and heat pipe assembly which reside immediately behind the FPA substrate. Each CCD module mounts to the curved FPA substrate only at the inserts. The graphite composite substrate is used to provide a stable thermoelastic platform for all

CCD modules. Heaters are mounted onto the ‘thermal spreader’ and are used to actively control the temperature of the FPA. Temperature drifts over time resulting from the changing sun solar angle are not expected to exceed  $0.1^{\circ}\text{C}$  per 12 hour period and when the active control system is factored in the actual temperature variability is expected to be considerably less than this value.

CCD modules are arranged on the FPA in a rotationally symmetrical orientation to ensure all stars are monitored in a consistent manner over time (e.g. before and after the quarterly  $90^{\circ}$  roll maneuvers). To minimize the degrading effects on the CCDs of very bright stars (i.e.,  $m_v < 9$ ), many of the brightest stars in the field of view are aligned to fall onto the FPA web light shield (see gap between modules in Figure 3). CCD modules are installed and removed exclusively from the front of the FPA, thereby not disturbing any part of the FPI.



*Figure 3 Top side view of Kepler FPA*

The photometer has been designed to allow a total optics plus FPA alignment tolerance budget of  $\pm 150\text{ }\mu\text{m}$ , which, in turn, enables the FPA to be assembled using a ‘bolt and go’ approach. That is, if the CCDs, CCD module components, and FPA substrate are manufactured to sufficient tolerance, then all components can be simply assembled together and the resultant stack up in tolerance will be within the allotted budget. Therefore, precise focus alignment is not required for each CCD or CCD module. The photometer has an overall focus mechanism on the primary mirror that is used to bring the entire FPA into optimal focus. It should be noted here that by design optimal focus results in a total system PSF (i.e. optics plus CCD) ranging from 4 to 7 pixels in diameter. This broad PSF is highly desired in

photometric applications such as *Kepler* [4] because it significantly reduces the sensitivity to intra-pixel variations and minimizes the number of stars that will saturate on the CCDs.

### 3. FOCAL PLANE INTERFACE

The Focal Plane Interface (FPI) consists of 13 electronics boards and one backplane, configured in a typical card cage arrangement. 11 boards are used to drive the 21 science CCD modules and 2 boards are used to drive the 4 fine guidance detectors. The body of the FPI is sealed from the photometer interior to minimize the possibility of outgassing contamination reaching the sensitive electro-optical components within the photometer. The FPI is vented to the exterior of the photometer through the use of a dedicated hose which runs along the length of one of the spider support leg.

Boards are installed and removed from the FPI exclusively from the rear of the FPI, thereby not disturbing any part of the FPA. Each of the 11 science module driver boards supplies all the clocks and biases to run two CCD modules, or 4 CCDs. The boards are designed and laid out in such a manner as to ensure that any credible single point failure will result in the loss of only one CCD module. Fully redundant power and control signals are routed to the FPI from the CCD Signal Processor (CSP) and the LVDS timing signals routed to the FPI are fully redundant from within the CSP. The 84 science CCD outputs are driven to the CSP from the FPI using low noise differential line drivers through individually shielded twisted pair cables. Figure 4 shows a schematic representation of the photometer electronics systems.

The CCD Signal Processor (CSP) is tasked with supplying all clocks and control signals to the FPI and with digitizing and storing data from all 95 million pixels during the 15 minute aggregation periods. Each channel on the CSP is composed of two memory banks arranged in a ping-pong configuration. So while 15 minute binned data is being read out of one bank (ping) the other bank (pong) is acquiring the next 15 minutes worth of data. The CSP also has the ability to detect and remove transient signal events caused by incident cosmic or solar radiation. Common timing signals generated within the CSP ensure that all 42 science CCDs are operated synchronously, which significantly reduces electrical crosstalk between the 84 CCD outputs. The fine guidance CCDs on the FPA run at a 10 Hz frame rates (non-synchronous with science CCDs), but the boards and wiring

associated with these CCDs are separate and decoupled from the science CCDs to minimize potential crosstalk issues. The Remote Photometer Electronics (RPE) and Solid State Recorder (SSR) perform other system level functions (not discussed in this work).

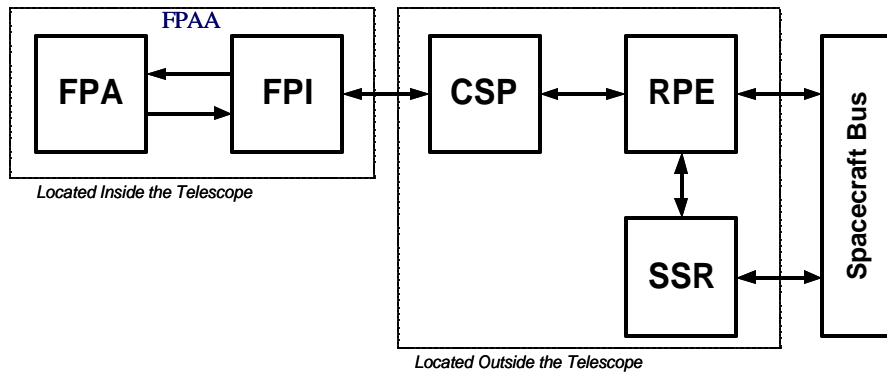


Figure 4 Block diagram of the Kepler photometer electronics

#### 4. CCD MODULE

Each science CCD module houses two CCD detectors on a common substrate. Electrical signals are routed from the CCD bondpads to a PCB located on the bottom side of the module substrate using high density, subminiature connectors and cables. Several surface mount decoupling capacitors reside on the PCB, in addition to the 51 pin main interface connector which mates to a similar connector on the FPA substrate. A field flattener lens resides above the CCDs and is supported using a four sided fixture. A captive screw is held in each of the 4 flexure support legs and is used to affix the CCD module to the FPA substrate from the front of the FPA. The legs provide mechanical support and the thermal path to the thermal spreader located on the back of the FPA.

Electrical signals are routed from the CCD bondpads to the PCB located on the bottom side of the module substrate using high density, subminiature connectors and cables. Several surface mount decoupling capacitors reside on the PCB, in addition to the 51 pin main interface connector. The main interface connector on the CCD modules mates with an opposite gender connector affixed to the FPA substrate.

The pinout of the CCD is symmetric about the row dimension and, therefore, both frontside and backside versions of the CCD can be

accommodated using the aforementioned packaging scheme (see Figure 6). The science CCDs operate in the backside illumination mode to yield high quantum efficiency over the 400 to 900 nm wavelength range of interest, to minimize intra-pixel variability and the effects of stellar variability in the UV and faint reddened background eclipsing binaries, and to provide additional flexibility in tailoring the point spread function (PSF).

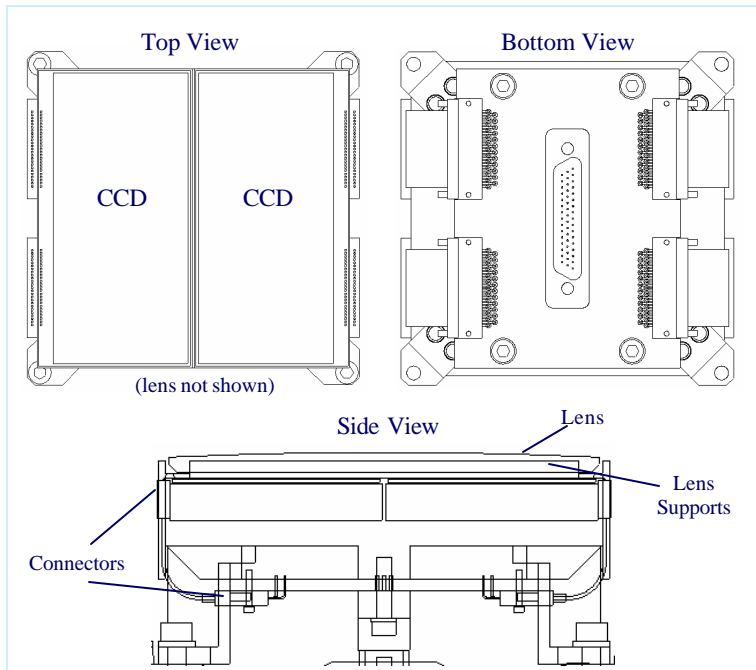


Figure 5 Schematic of a single Kepler science CCD module

Two CCD manufacturers, Marconi Applied Technologies and Semiconductor Technologies Associates, have been selected to supply the science grade CCD detectors for the *Kepler* mission. Each vendor will be tasked with supplying 30 flight grade CCDs, in addition to several mechanical, frontside evaluation grade, and engineering grade CCDs.

Each *Kepler* science detector is a CCD-based full frame device with 2200 columns and 1024 rows, as depicted in Figure 6. A four-phase architecture is employed in both the serial and parallel CCD registers to maximize charge capacity ( $> 1\text{Me}^-$ ) and minimize clocking induced artifacts. Each pixel is  $27\text{ }\mu\text{m} \times 27\text{ }\mu\text{m}$ . A vertical injection structure is included and may be used to pre-flush the entire photoactive area or pre-fill select portions only.

## 5. FPA PERFORMANCE

The *Kepler* application is somewhat unique for a space based telescope in that the mission involves staring at the same image scene for 4 years. In addition, because relative differential rather than absolute photometry is being performed to detect transit events on the time scale of 2 to 16 hours, slow changes over time in optical, CCD and electronics performance are easily identified and removed from the data by detrending.

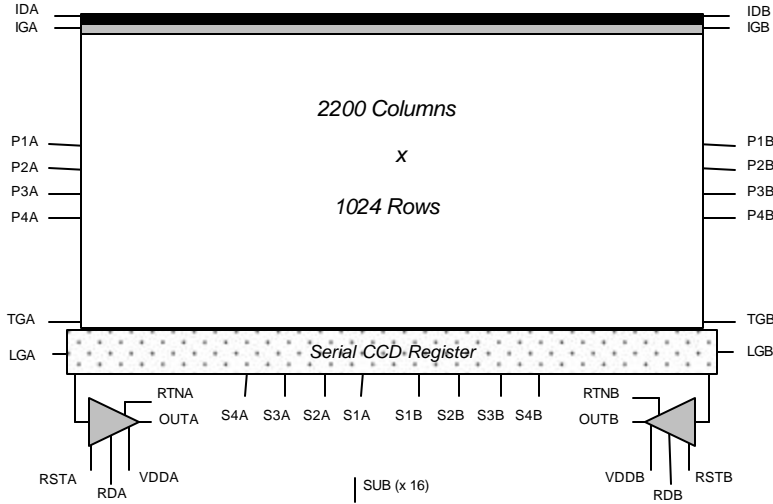


Figure 6 Block diagram of the Kepler CCD detector

CCD performance model simulations have been run for several possible CCD operating modes and configurations [5] and the results indicate that the degradation in charge transfer efficiency resulting from exposure to the space radiation environment will not significantly degrade the performance of the CCDs over the 4 year lifetime. This is due principally to the fact that the radiation induced traps reach a steady state population at the  $-90^{\circ}\text{C}$  operating temperature, a result of the static imaging application and the fact that the trap emission time constant is 4 seconds whereas the integration period is only 2.5 seconds. At higher temperatures, where the trap emission time constant is much less than the integration period, the trap population does not reach a steady state but the impact of degraded CTE on each star in the FOV remains relatively constant over time and again there is no significant impact on the ability to perform relative photometry. The preliminary instrument design placed the CCD operating temperature at  $-90^{\circ}\text{C}$  but recent analysis appears to indicate that the CCDs could operate as

warm as  $-60^{\circ}\text{C}$  and possibly higher whilst enabling the photometer to meet all performance requirements at end-of-life.

System level signal-to-noise analysis shows that stellar variability is the dominant noise source for the brighter stars ( $m_v < 12$ ) and photon shot noise for the fainter stars ( $m_v = 12$ ). This, in turn, permits the CCD and FPI noise budgets to be relatively high when compared to other space-based CCD instruments. For example, at the nominal integration period of 2.5 s and pixel rate of 3M pixels/s, the maximum read noise specification for the CCDs is 25 e<sup>-</sup> rms.

## 6. CONCLUSIONS

The preliminary design of the *Kepler* FPAA has been discussed. While design trades and analyses are expected to continue well into 2003, and minor changes in materials and processes will likely occur, the basic design of the *Kepler* FPAA is not expected to deviate significantly from that presented herein. Specific design trades currently underway are investigating the impact on photometer performance of raising the FPA operating temperature above the baseline  $-90^{\circ}\text{C}$  level and investigating the use of alternative materials for the FPA substrate.

## 7. REFERENCES

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